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Particulate Control Mobile Test Units Second Year's Operation

Monsanto Research Corp, Dayton, Ohio

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16. ABSTRACT The report summarizes the second year's operation of EPA-owned mobile test units. Unit use divides into two principal areas: (1) three units (baghouse, electrostatic precipitator (ESP), and wet scrubber) are designed for use in the field to study the applicability of different methods for controlling fine particulate emitted from a wide variety of sources; and (2) a fourth unit (energy van) is designed to demonstrate the feasibility of unconventional energy supply systems to support residential and commercial buildings. Results from baghouse tests on a kraft mill lime recovery kiln indicate an overall, integrated collection efficiency of 99.98+ wt %. Based on collection efficiency alone, a high level of control can be afforded by a baghouse on lime kiln particulate emissions. However, based on projected operating problems due to high moisture content of the gas, baghouse control of a lime recovery kiln is not recommended. Mobile scrubber unit operation during the year was confined to start-up field testing and correction of mechanical and operating difficulties. The ESP unit is still under construction. The newly acquired energy van has not yet undergone testing.

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Dust Collectors	Scrubbers	Fine Particulate	13A	07A
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PARTICULATE CONTROL MOBILE TEST UNITS: SECOND YEAR'S OPERATION

by

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Contract No. 68-02-1816
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ABSTRACT

This report summarizes the second year of operation for EPA-owned mobile test units. Due to the recent contractual acquisition of a mobile unit designed for energy R&D work, usage divides into two principal areas.

Three units (baghouse, wet scrubber, and electrostatic precipitator) are designed to be used in the field to study the applicability of different methods for controlling fine particulate emitted from a wide variety of sources. A fourth unit (energy van) is designed to demonstrate the feasibility of unconventional energy supply systems to support residential and commercial buildings.

Three units are described herein: (1) fabric filter (baghouse), (2) wet scrubber, and (3) energy van. The fourth unit (electrostatic precipitator) is still under construction.

Results from baghouse tests on a kraft mill lime recovery kiln indicate an overall, integrated collection efficiency of 99.98+ wt %. On the basis of collection efficiency alone, a high level of control can be afforded by a baghouse on lime kiln particulate emissions. However, on the basis of projected operating problems due to high moisture content of the gas, baghouse control of a lime recovery kiln is not recommended.

Baghouse control of a black liquor recovery boiler would also be discouraged on the basis of high moisture content in the gas, although no collection efficiency data were obtained for such control.

Operation of the mobile scrubber unit during the year was confined to startup field testing and correction of mechanical and operating difficulties.

The energy van, a newly acquired mobile unit, has not undergone testing to date.

CONTENTS

Abstract		iii
Figures		vi
Tables		vi
Acknowledgements		vii
1	Introduction and Objectives	1
2	Conclusions	3
3	Review of Operations	4
	3.1 Baghouse Unit	4
	3.1.1 Background	4
	3.1.2 Plymouth, N.C. Testing	5
	3.1.3 Baghouse Repackaging and Upgrading	22
	3.2 Mobile Scrubber Unit	22
	3.2.1 Background	22
	3.2.2 Events of Second Year	24
	3.3 Mobile Energy Van	24
References		31

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FIGURES

Number		Page
1	Schematic of kraft pulping process flow	6
2	Relative position of baghouse to lime kiln	7
3	Relative position of baghouse to recovery boiler	9
4	Current baghouse enclosure	23
5	End view - baghouse	23
6	External view of mobile scrubber unit	25
7	Mobile scrubber unit process area	26
8	Sieve tray column	27
9	Scrubber flow schematic	28
10	Energy van - side view	29
11	Energy van - interior living area	29
12	Energy van - fuel delivery system	29

TABLES

1	Gas and Flue Characteristics at Lime Kiln	7
2	Gas and Breaching Characteristics at Recovery Boiler	8
3	Composition of Flyash from Boiler No. 3	9
4	Original Plymouth Test Plan	10
5	Bag Characteristics	11
6	Actual Run Conditions	12
7	Impactor Mass Resultants	16
8	Size and Fractional Efficiency Results	17
9	Pressure Drop Results	18

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SECTION 1

INTRODUCTION AND OBJECTIVES

The purpose of EPA Contract No. 68-02-1816 is to provide the operational effort required to obtain field laboratory and pilot plant test data from EPA-owned equipment and systems. Contract operations are currently divided into four areas:

MOBILE TEST UNITS

The mobile test units consist of truck-mounted items of conventional dust collection equipment: fabric filter (baghouse), venturi scrubber, sieve tray scrubber, and electrostatis precipitator (not yet operational). The main objective is to assess the ease/difficulty associated with this type of equipment in controlling particulate-laden gas streams of varying characteristics obtained at different types of emission sources in the field.

AERODYNAMIC TEST CHAMBER

This wind-tunnel-like chamber provides for gas movement in a wide range of velocities at temperatures from ambient to above 149°C (300°F) and accommodates a broad spectrum of gas composition and particulate loading. The objectives for its use are calibration and testing of fine particulate measurement equipment. It is also being used as a source of test dust for the mobile field units.

PILOT SO_x SCRUBBER

This unit consists of twin 23-cm (9-inch) diameter scrubbers and associated systems capable of several types of scrubbing modes operating in parallel or series. The objective of their operation is to determine quick, easy, inexpensive solutions to operating and technical problems encountered in the development of full-size SO_x scrubbing systems.

ENERGY VAN

The EPA energy van is a towable mobile home containing an energy supply system that utilizes environmentally clean and energy-conserving components. These components include fuel cells, a solar energy collector, a heat pump, and catalytic appliances. The objective of the mobile system is to develop and demonstrate an energy supply system for residential and commercial buildings which could cut pollution and energy consumption by as much as 50%.

The aerodynamic test chamber and pilot scrubber system are semipermanent installations at the Environmental Research Center (ERC) in Research Triangle Park, North Carolina. Although the truck-mounted units use this location as a service base, the majority of their operating time is spent in the field at various plant sites throughout the country. The energy van has been temporarily located at ERC for a performance testing period of approximately 1 year.

The four operational areas represent, to varying degrees, different program interests and different groups or sections within the Industrial Environmental Research Laboratory. The contractor's objective is to fulfill the needs of each interest within the contract scope. Thus, the level of involvement varies in each operational area. For example, in the areas of the aerodynamic test chamber and pilot SO_x scrubbers, the activities of program and test planning and interpretation of results are mainly conducted by EPA personnel. The contractor schedules and executes the test plans under specified conditions, and collects and reduces data to usable form. The nature of the current program, expecially for the pilot SO_x scrubber project, dictates this type of relationship. In the mobile test unit area, however, the contractor is also largely responsible for developing the test plans and interpreting the results obtained.

This report primarily summarizes operation of and experience with the mobile baghouse and scrubber units during the second contract year.

SECTION 2

CONCLUSIONS

During the one completed mobile unit field test (baghouse operating on effluent from a kraft mill lime recovery kiln), all cleaning mode/bag type combinations performed at maximum collection efficiency, both integrated mass and fractional, within the test regimen.

Overall, integrated collection efficiency was 99.98+%. Overall averages of mean fractional efficiencies by size range were as follows:

Size, μm	Efficiency, %
1-3	99.815
4-6	99.814
7-10	99.918

On the basis of collection efficiency alone, a high level of control of lime recovery kiln emissions can be afforded by a baghouse.

On the basis of bag differential pressure at comparable operating conditions, shake cleaning was significantly more efficient than reverse flow cleaning.

On the basis of projected operating problems due to high moisture content in the gas, baghouse control of a lime recovery kiln is not recommended.

Although no collection efficiency data were obtained for it, baghouse control of a black liquor recovery boiler would also be discouraged on the basis of high moisture content in the gas.

SECTION 3

REVIEW OF OPERATIONS

3.1 BAGHOUSE UNIT

3.1.1 Background

The mobile fabric filter system (baghouse unit) was designed and fabricated by GCA/Technology Division, Bedford, Massachusetts. The unit was mounted on a 1.36-metric-ton (1-1/2-ton) truck and is described at length in GCA reports.[1,2] Briefly, it has the following capabilities:

- Filtration can be conducted at cloth velocities as high as 0.102 m/s (20 fpm) with a pressure differential up to 4.98 kPa (20 in. water) and at a gas temperature up to 288°C (550°F).
- The mobile system is adaptable to cleaning by mechanical shaking, pulse jet, or low pressure reverse flow, with cleaning parameters which vary over broad ranges.
- The system can be operated in a series filtration mode.
- One to seven filter bags of any medium, 1.22 m to 3.05 m (4 ft to 10 ft) long and up to 0.3 m (12 in.) in diameter, can be used.
- Automatic instruments and controls enable 24-hour operation of the system.

After brief field tests, the unit was delivered to present contractor personnel for use in a field testing program for the Industrial Environmental Research Laboratory of EPA.

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[1]Hall, R. Mobile Fabric Filter System - Design Report. GCA/Technology Division. Contract No. 68-02-1075. October 1974.

[2]Hall, R. Mobile Fabric Filter System - Final Report. GCA/Technology Division. Contract No. 68-02-1075. May 1975.

For several reasons, the baghouse unit, as received, required preliminary "dry run" testing at the RTP Environmental Research Center, and intensive shakedown tests in the field under severe conditions. The dry run tests at RTP were directed at operational checks of system components and training of new operators.

The unit was then given shakedown tests in the field on a pulp mill lime recovery kiln. After a brief return to RTP for refurbishing, the unit was taken to Sunbury, Pennsylvania for tests on Pennsylvania Power and Light Company's Shamokin Dam, coal-fired generating station on 16 December 1974. These tests lasted through 26 February 1975.

On completion of these tests, about 2 months were required to refurbish the unit and sample trains, after which the unit was placed at a lime recovery kiln at Weyerhauser Corporation's pulp mill in Plymouth, North Carolina from 21 April 1975 to 19 September 1975. Results of that test are summarized below.

3.1.2 Plymouth, N.C. Testing

Two test sites at the Weyerhauser pulp mill were initially considered: (1) exhaust duct of the lime recovery kiln, and (2) exhaust duct of the black liquor recovery boiler. Difficulties encountered throughout the program limited the test to the lime kiln only.

3.1.2.1 Test Site Description--

Figure 1 shows, in general, typical kraft pulping process flow, wherein the major sources of particulate emission are seen to be the recovery boiler and lime kiln.

3.1.2.1.1 Lime kiln--At the Plymouth mill the lime recovery area included three rotary calciners essentially identical in all respects with rated capacity of 109 metric tons (120 tons) per day lime. Testing was conducted at No. 3 kiln solely because of accessibility. Effluent for testing was taken from the hood on the exhaust end of the kiln through a 63.5-mm (2-1/2-in.) diameter curved probe that extended into the gas stream 0.61 m (24 in.). The open end of the probe faced the oncoming gas. The slipstream so obtained was conducted to the baghouse through approximately 16.8 m (55 ft) of insulated, 63.5-mm diameter pipe. Characteristics of the slipstream duct were as follows:

I.D. - 61.7 mm (2.43 in.)
Area - 0.00287 m^2 (0.0309 ft^2)
Length - 16.8 m (55 ft)
Test flow range - 3.68×10^{-2} to 6.18×10^{-2} m^3/s (78 to 131 acfm)
Test flow velocity - 12.8 to 21.3 m/s (42 to 70 fps)
Test pressure drop - 0.5 to 1.2 kPa (2 to 5 in. w.c.)

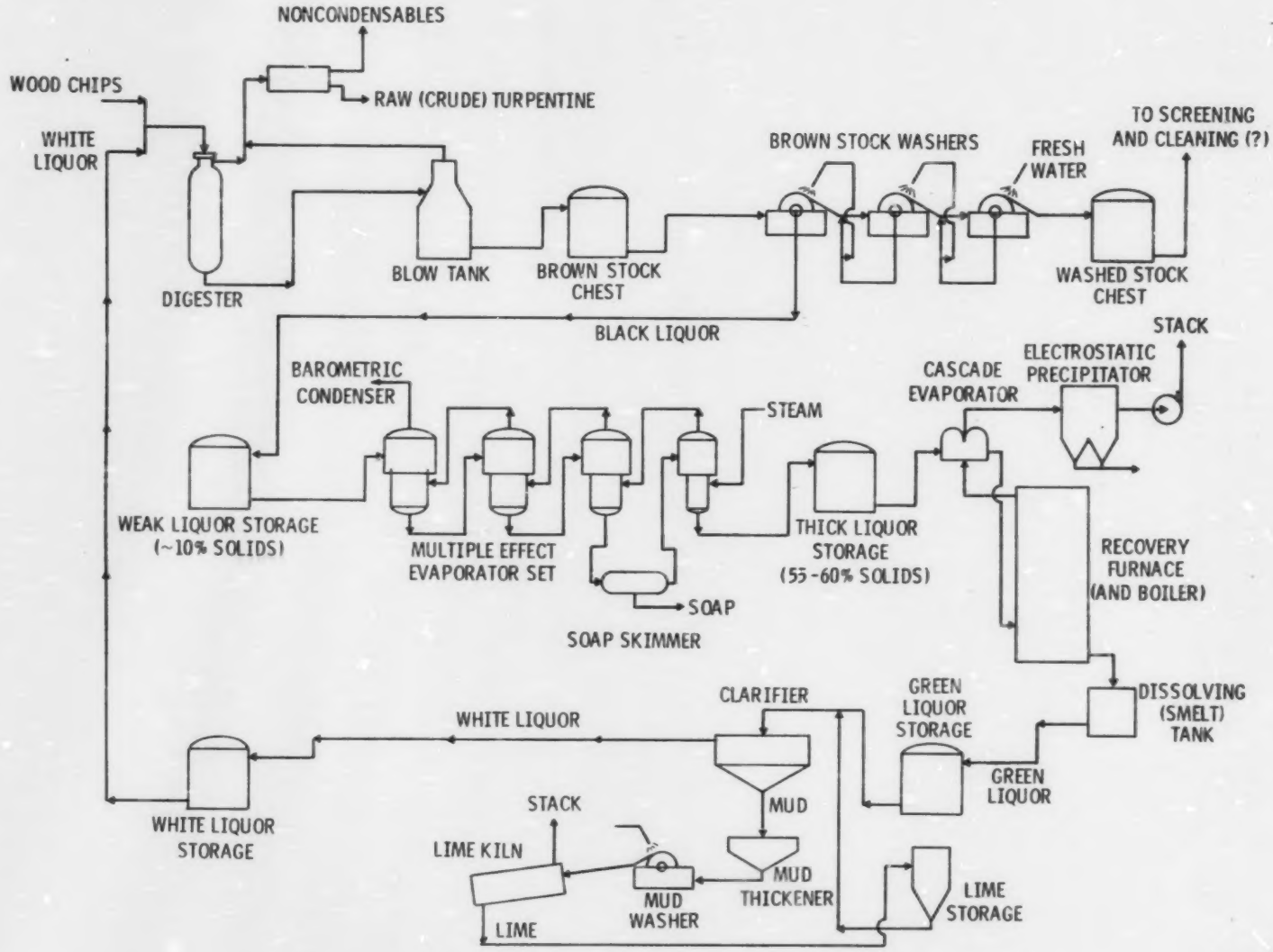

Figure 1. Schematic of kraft pulping process flow.

Characteristics of the exhaust gas and flue at the slipstream port are shown in Table 1. Figure 2 indicates relative equipment positions at the site.

TABLE 1. GAS AND FLUE CHARACTERISTICS AT LIME KILN

Gas composition, wet basis	
O_2	7.1%
CO_2	15.4%
H_2O	25.0%
N_2	52.5%
Mol. wt. - wet basis	28.25
dry basis	31.66
Grain loading	7.25 g/m^3 (3.17 avg., gr/dscf)
Temperature	260°C-299°C (500°F-570°F)
Dew point	65.6°C (150°F)
Static pressure	0.075 kPa (0.30 in. w.c.)
Density - wet (0°C)	1.26 kg/m^3 (0.0788 lb/ft^3)
(299°C)	0.60 kg/m^3 (0.0376 lb/ft^3)
dry (0°C)	1.46 kg/m^3 (0.0909 lb/ft^3)
(299°C)	0.70 kg/m^3 (0.0434 lb/ft^3)
Hood section (perpendicular to flow)	2.37 m^2 (25.5 ft^2)
Superficial gas velocity	6.4 m/s (21 ft/s)
Flow	15.2 m^3/s (32,160 acfm)

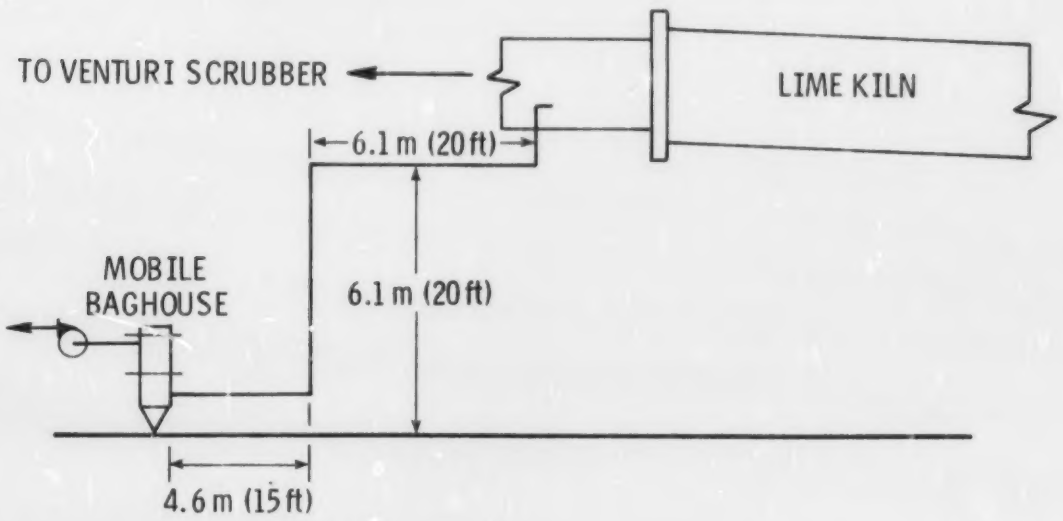

Figure 2. Relative position of baghouse to lime kiln.

It is not surprising that there was no indication of free sulfur dioxide in the presence of such high loading of lime dust. Sulfur present in the kiln feed either carried over as undecomposed calcium salt ($CaSO_3$ and/or $CaSO_4$) or formed through combination, or recombination, in the gas stream leaving the kiln. Aqueous solution (slurry) of the exhaust solids showed pH in the range of 10.0 to 12.0.

3.1.2.1.2 Recovery boiler--Of the two boilers accessible for testing (Nos. 3 and 4), No. 3 was selected because of greater accessibility. Nominally, operation of both boilers was the same. This subsequently proved untrue, and an unsuccessful attempt was made to test No. 4 boiler. In either case, entry to the breaching was by a 63.5-mm (2-1/2-in.) diameter probe extending 0.61 m (24 in.) into the gas stream. The entry port was located approximately midway between the cascade evaporators and electrostatic precipitator (refer to Figure 1). Gas for test purposes was taken to the baghouse through 41.1 m (135 ft) of 63.5-mm diameter insulated ducting. Characteristics of the slipstream duct were as follows:

I.D. - 61.7 mm (2.43 in.)
Area - 0.00287 m^2 (0.0309 ft^2)
Length - 41.1 m (135 ft)
Test flow range - 3.68×10^{-2} to 6.18×10^{-2} m^3/s (78 to 131 acfm)
Test flow velocity - 12.8 to 21.3 m/s (42 to 70 fps)
Test pressure drop - 0.5 to 1.2 kPa (2 to 5 in. w.c.)

Characteristics of the exhaust gas and breaching at the slipstream port are shown in Table 2. Figure 3 shows relative equipment positions at the site.

TABLE 2. GAS AND BREACHING CHARACTERISTICS AT RECOVERY BOILER

Gas composition, wet basis	
O_2	9.5%
CO_2	10.6%
H_2O	24.0%
N_2	55.9%
Mol. wt. - wet basis	27.67
dry basis	30.74
Grain loading	7.5 g/m^3 (3.3 avg., gr/dscf)
Temperature	177°C (350°F)
Dew point	64°C (148°F)
Static pressure	#3 boiler - 0.6 kPa (-2.5 in. w.c.)
	#4 boiler - 1.4 kPa (-5.5 in. w.c.)
Density - wet (0°C)	1.23 kg/m^3 (0.0771 lb/ft^3)
(299°C)	0.67 kg/m^3 (0.0417 lb/ft^3)
dry (0°C)	1.37 kg/m^3 (0.0856 lb/ft^3)
(299°C)	0.74 kg/m^3 (0.0463 lb/ft^3)
Breach section	4.16 m^2 (44.8 ft^2)
Superficial gas velocity	7.8 m/s (25.6 fps)
Flow	32.48 m^3/s (68,813 acfm)

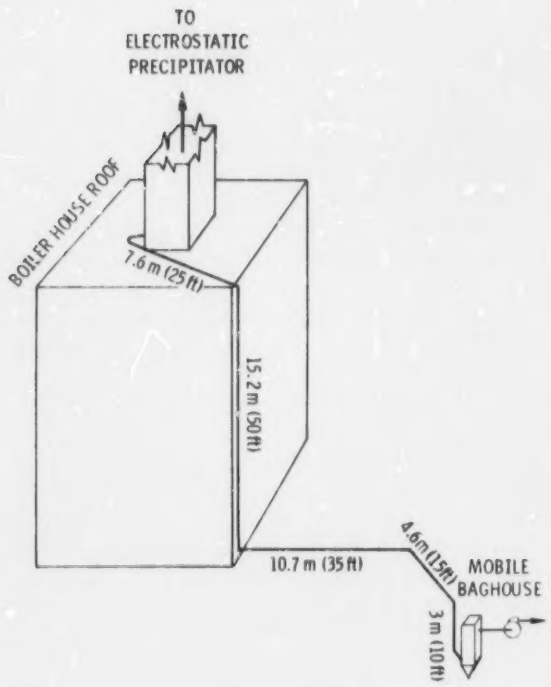

Figure 3. Relative position of baghouse to recovery boiler.

Again, there was no indication of free sulfur dioxide in the flue gas. Inorganic salts in black liquor are mainly those of sodium. Table 3 shows analysis of the solids emitted from the recovery boiler. Allowing for some error in analysis, results indicate the solids are about 17% Na_2SO_3, 45% Na_2SO_4, 40% Na_2CO_3, and 2-3% NaOH. Solution of the solids showed pH 10.6.

TABLE 3. COMPOSITION OF FLYASH FROM BOILER NO. 3

Na_2SO_3, mg/g	173
Na_2SO_4, mg/g	455
NaOH, mg/g	35
Na_2CO_3, mg/g	420
pH	10.6
Moisture, %	5
Moisture, 24-hr regain, %	1.5

3.1.2.2 Equipment Operating Cycles--
Pulping operations, especially of the magnitude at Weyerhauser's Plymouth Mill, normally are stable, steady-state processes. As noted in Figure 1, surge capacity is provided throughout the

system. These chests and tanks are maintained at levels that will permit a period of continued operation on either of their sides in the event of equipment outage. Nominally, this surge capacity is adequate for the time required to get equipment back on line. Aside from process upsets caused by equipment malfunction, the only "short" term cycles in the overall system occur at the digester end of the process where digesters are blown in a cyclic manner.

Consequently, the lime kilns, in particular, operate in a very stable mode, unless outage occurs at the kiln itself. In the present case, plant operating personnel assured steady-state operation at the test kiln by accommodating rate changes on the two remaining kilns. So far as could be determined, the test kiln ran steadily at capacity throughout testing, although the tests had to be interrupted on two occasions because of kiln outage.

While similar stable operation was expected at the black liquor recovery boilers, such was not the case. At the boiler selected for testing, erratic operation derived from frequent, unpredictable outages caused by malfunctioning of electrostatic precipitators and induced draft fans. At the alternate boiler, No. 4, erratic operation was due either to poor control of combustion air rates or unstable operation of the cascade evaporator set. The result was a heavy concentration of small beads of tarry black liquor taken into the slipstream to the baghouse. This combination of atypical performances contributed in large measure to the frustration of testing at the recovery boilers.

3.1.2.3 Test Plan--
The Plymouth testing scheme is shown in Table 4. Bag fabrics selected were woven and felted Nomex, which are described in Table 5. For each set of test parameters, new bags were installed and conditioned for 24 hours at an air-to-cloth (A/C) ratio of 1.5×10^{-2} m/s (3 fpm).

TABLE 4. ORIGINAL PLYMOUTH TEST PLAN[a]
(Lime kiln recovery boiler, Weyerhauser Corporation)

Cleaning mode	A/C ratio, m/s		Filtration period, min		Cleaning period, s	
	Low	High	Low	High	Low	High
Shake	0.01(0.015)		30		5	
	0.01(0.015)			50	5	
		0.03(0.025)	30		5	
Reverse	0.01(0.015)		30		5(20)	
	0.01(0.015)			50	5(40)	
	0.01(0.015)		30			20(40)
		0.03(0.025)	30		5	

[a]Woven and felted Nomex both tested at each condition shown.

TABLE 5. BAG CHARACTERISTICS[a]

MATERIALS

Fabric	Count W	Count F	Weave	Weight, oz/yd^2	Permeability, cfm/ft @ 2 in. H_2O
Nomex-woven	98	99	3 x 1 twill	4.5	18
Nomex-felt	---		needled	14	40

CONSTRUCTION

Cleaning mode	Diameter, in.	Length, in.	Other
Shake	5 9/16	72	2-in. cuff and bolt rope one end, loop one end
Reverse	5 9/16	72	2-in. cuff and bolt rope one end, loop one end; three spreader rings: middle and one each 18 in. from top and bottom

[a]All bags were manufactured by Globe Albany Corporation, Buffalo, New York. The materials specifications shown are theirs.

The test scheme has two restraints. First, maximum pressure drop across the bags is limited to 2.5 kPa (10 in. w.c.) by instrument range. Second, flow through the unit must be high enough to maintain the gas above its dew point. In Table 4, figures in parentheses in the A/C columns are values resulting from these restraints. With felted Nomex bags in reverse mode, the only viable A/C value was 1.5×10^{-2} m/s. In the cleaning period columns, parenthetical figures are values associated only with felted Nomex bags. Other baghouse parameters employed during the tests are shown in Table 6.

The test plan further considered use of mass efficiency at each set of conditions as a quick screening device, since experience at Sunbury showed such sampling could be done in a matter of minutes. After review of such mass efficiency results, the condition(s) showing best efficiency would then be reimposed and sampled for size distribution. The intent was to limit the time-consuming operation of size distribution sampling. However, filtration efficiency at Plymouth was so great that a period of hours was required to collect sufficient samples for reliable measurement. The mass efficiency screening approach has another time-consuming aspect; namely, the baghouse must be rearranged back to a preceding configuration, and bags must be reinstalled and conditioned. Consequently, mass sampling was abandoned and replaced by impactor sampling at all test conditions.

TABLE 6. ACTUAL RUN CONDITIONS

Shake mode	
Filtration period	30, 50 min
First pause	30 s
Cleaning period	5 s
Second pause	30 s
Shake frequency	7 cps
Amplitude	22.2 mm (0.875 in.)
Shaker-arm acceleration	43.1 m/s^2 (4.4 g's)
Bag tension	0.68 kg (1.5 lb)
A/C	0.015, 0.025 m/s (3, 5 fpm)
Reverse mode	
Filtration period	30, 50 min
First pause	30 s
Cleaning period	5, 20, 40 s
Second pause	30 s
Bag tension	0.68 kg (1.5 lb)
A/C	0.015, 0.025 m/s (3, 5 fpm)
R.F. air temperature	113°C (235°F)
R.F. air flow	4.5 x 10^{-2} m^3/s (95 acfm)

In subsequent data tabulation, test conditions are coded as follows (some nonmetric units were used in original data tabulation and these are included below):

Cleaning mode: Shake - S
Reverse - R

Bag fabric: Woven Nomex - WN
Felted Nomex - FN

Example: S-WN-3-30-5

First letter - cleaning mode
Second set of letters - bag fabric
First number - A/C, fpm
Second number - filtration period, min
Third number - cleaning period, s

3.1.2.4 Sampling Procedures--
For test purposes, Brink® impactors were used for inlet gas sampling, and Andersen impactors for outlet gas sampling.

Static and velocity pressure measurements for determining gas velocities in inlet and outlet ducts were made with a standard pitot tube. The sampling duct was 63.5 mm (2.5 in.) in diameter, and measurements were made at the average velocity point. EPA Method 4 and Orsat analysis were used for determining gas composition and gas density calculations.

3.1.2.4.1 Sampling duration--The lengths of sampling periods were regulated by mass concentration in the gas, size distribution, and flow rate through the impactor. Sample periods were first estimated from nominal time, grain loading, and flow rate graphs, and then adjusted so that a maximum of 10 mg of dust was deposited on any one stage.

3.1.2.4.2 Impactor preparation--After assembly, impactors were leak tested at 50.7 kPa (15 in. Hg) and wrapped with heating tape covered with insulation. A thermocouple was inserted between the heating tape and impactor body to indicate impactor surface temperature. Warmup periods lasted 30 min for the Brink impactor and 20 to 30 min for the Andersen impactor. Temperature controllers maintained and indicated impactor temperatures.

3.1.2.4.3 Sampling operation--Each complete sampling train was leak tested at 50.7 kPa (15 in. Hg) before start of sampling. After sufficient warmup, the appropriate probe was inserted into the duct and connected to the impactor, and sampling was begun.

With the Andersen impactor, insertion and removal of the probe was accomplished while the baghouse was in the bypass condition. This practice had two advantages: (1) elimination of unwanted collection of dust in the probe (or impactor) before and after the sampling period, and (2) provision for incremental cycle sampling. The latter ensured representative dust loading by negating the substantial change in effluent concentration with respect to elapsed time from the start of the filtering cycle.

Brink impactor--A sixth stage was added to extend collection capability to a smaller size range. The external precollector cyclone formerly used was replaced by a cyclone integral with the impactor body. This effectively eliminated line losses between the external cyclone and the impactor, and simplified preparation and disassembly of the device.

While probe losses are inherent in extractive sampling techniques, their extent was reduced by selection of the largest probe size compatible with isokinetic sampling. Probe losses were typically about 10%, with occasional values up to 50%.

Andersen impactor--In view of difficulties previously encountered wherein the fiber glass substrates suffered significant weight gain through reaction with SO_2 in the stack gas, Andersen substrates were preconditioned for 24 hours in filtered stack gas from the lime kiln. No measurable weight gain was observed from preconditioning. In retrospect, this is logical since it was subsequently shown that SO_2 is not present in the lime kiln effluent gas.

In this testing episode, Andersen backup filters were employed to extend the collection capability to a smaller size range than was permitted during tests at Sunbury.

The sampling period had to be extended to 8 hours in order to obtain measurable amounts of dust on the substrates. Though measurable, such weight gain was typically less than 2 mg/stage.

The high moisture content of the kiln gas dictated addition of a condenser just before the drying columns in the sample train. The protracted sampling period required frequent drainage of the condenser and replacement of the drying columns, which was performed during the bag cleaning period when the sample train was inactive.

3.1.2.5 Data Reduction Procedures--
The processing of raw data to reported results was accomplished by computer through a program modified to include virtually all calculations formerly executed manually.

Impactor sample data input to the computer was unchanged and consisted of:

- Weight gain per stage, mg
- Sample period, min
- Particle density, g/cc
- Gas temperature, °F
- Barometric pressure, in. Hg
- Impactor pressure drop, in. Hg
- Impactor flow rate, cfm
- Upper size estimate, μm
- Flue gas composition, component fraction

Output from the modified program consisted of:

- Total grain loading, gr/acf and gr/sdcf
- D_{50} size per stage, μm
- Mass per stage, g (also an input)
- Cumulative gr/acf by stages
- Cumulative mass by stages, g
- Percent cumulative mass by stages
- Grain loading per stage, gr/sdcf
- dM/dlogD
- Particle geometric mean diameter per stage
- *• Plot of cumulative distribution
- *• Tabulation of fractional efficiency and penetration
- *• Plot of fractional efficiency

The output items noted by asterisk are former manual operations. The major work-saving step in the program is that which provides the tabulation, at preselected particle size, e.g., 1, 2, 3, etc.

and the plot of fractional efficiency. Previously, dM/dlogD vs. GMD size was plotted manually for each inlet and outlet sample, and fractional efficiency at 1, 2, 3, etc. μm was calculated manually and plotted for each test run. These operations are now performed by the computer.

Not addressed before is the fact that particle size reported relates to "aerodynamic diameter." This represents the diameter of a sphere of unit density (1.0 g/cc) attaining, at low Reynolds numbers, the same final settling velocity as the real particle. The rationale for selection of aerodynamic diameter stems from the desire to normalize, or standardize, particle size independent of real particle density and thus facilitate comparison of fractional efficiencies between different types of sources wherein real particle densities vary significantly. The major difference in use of unit compared to actual density is a shift of particle size related curves toward the lower end of the size range.

3.1.2.6 Results and Discussion--
Table 7 shows grain loading in the gas entering and leaving the baghouse, and collection efficiency and penetration values for each set of test conditions. The test sets fall into four major groups by cleaning mode and bag type:

- Shake/woven Nomex
- Shake/felted Nomex
- Reverse/woven Nomex
- Reverse/felted Nomex

Cursory inspection of Table 7 suggests essentially equal performance in the four combinations. This is generally supported by the values of the average mean penetration, except in the case of shake/felted Nomex. Inspection of test data for this case reveals that at one test condition (S-FN-3-50-5), inlet grain loading was abnormally low, differing from the mean by a factor of about 15. At another test condition (S-FN-5-30-5), grain loading in was inconsistent between the duplicate samples. Thus, it is not clear whether the apparent discrepancy in the average mean penetration value for the shake/felted Nomex combination is due to inconsistent test conditions or is a real function of this particular combination. More credence is allotted the former possibility, and the tendency is to remain with the statement that collection efficiency overall was insensitive to changes in the test conditions imposed. This observation of insensitivity within the test regimen suggests that collection performance is at, or approaching, a maximum value.

The suggestion gains support on examination of fractional efficiency results in Table 8. These results do indicate that fractional collection efficiency is size dependent, but penetration is less than 1% for (aerodynamic) diameters of 1 μm to 10 μm almost without exception. Consequently, it appears that, at all

TABLE 7. IMPACTOR MASS RESULTS

Run	Grain loading, g/m^3 (gr/sdcf) In	Grain loading, g/m^3 (gr/sdcf) Out	Collection efficiency, %	Penetration, %
S-WN-3-30-5	8.65(3.78)	0.00291(0.00127)	99.97	0.0336
	8.65(3.78)	0.00318(0.00139)	99.96	0.0368
S-WN-3-50-5	7.83(3.42)	0.000191(0.0000835)	99.99	0.00244
	2.79(1.22)	0.000149(0.0000649)	99.99	0.00532
S-WN-5-30-5	2.33(1.02)	0.000359(0.000157)	99.98	0.0154
	4.39(1.92)	0.00130(0.000569)	99.97	0.0300
Average	5.77(2.52)	0.00135(0.000589)	99.98	0.0233
S-FN-3-30-5	6.86(3.00)	0.000613(0.000268)	99.99	0.00893
	6.86(3.00)	0.000897(0.000392)	99.99	0.0130
S-FN-3-50-5	0.597(0.261)	0.000831(0.000363)	99.86	0.139
	0.309(0.135)	0.000570(0.000249)	99.82	0.184
S-FN-5-30-5	4.35(1.90)	0.00220(0.000963)	99.95	0.0507
	8.21(3.59)	0.00563(0.00246)	99.93	0.0685
Average	4.53(1.98)	0.00179(0.000783)	99.96	0.0395
R-WN-3-30-5	11.2(4.91)	0.00102(0.000444)	99.99	0.00904
	8.58(3.75)	0.00281(0.00123)	99.97	0.0328
R-WN-3-30-20	6.80(2.97)	0.00110(0.000482)	99.98	0.0162
	5.95(2.60)	0.00105(0.000459)	99.98	0.0176
R-WN-5-30-5	24.9(10.9)	0.00118(0.000516)	99.99	0.00471
	5.84(2.55)	0.00113(0.000492)	99.98	0.0193
R-WN-3-50-5	5.88(2.57)	0.000755(0.000330)	99.98	0.0128
	5.95(2.60)	0.00146(0.000638)	99.97	0.0245
Average	9.40(4.11)	0.00131(0.000574)	99.99	0.0140
R-FN-3-30-20	8.56(3.74)	0.000931(0.000407)	99.99	0.0109
	4.97(2.17)	0.00112(0.000490)	99.98	0.0226
R-FN-3-50-40	6.80(2.97)	0.000490(0.000214)	99.99	0.00721
	9.15(4.00)	0.00166(0.000726)	99.98	0.0182
R-FN-3-30-40	13.9(6.08)	0.00166(0.000726)	99.99	0.0119
	7.94(3.47)	0.00180(0.000788)	99.98	0.0227
Average	8.56(3.74)	0.00128(0.000559)	99.99	0.0149

TABLE 8. SIZE AND FRACTIONAL EFFICIENCY RESULTS

Run	Mass median diameter, μm		Fractional efficiency		Mean fractional efficiency		
	In	Out	Min.	Max.	1 - 3 μm	4 - 6 μm	7 - 10 μm
S-WN-3-30-5	7.7	3.6	99.61 @3	99.99 @10	99.66	99.85	99.97
	7.7	1.1	99.28 @3	99.99 @10	99.46	99.81	99.99
S-WN-3-50-5	7.5	0.46	-[a]	-[a]	-[a]	-[a]	-[a]
	7.4	0.45	-[a]	-[a]	-[a]	-[a]	-[a]
S-WN-5-30-5	7.4	0.5	-[a]	-[a]	-[a]	-[a]	-[a]
	8.3	0.7	-[a]	-[a]	-[a]	-[a]	-[a]
S-FN-3-30-5	7.7	0.5	99.89 @1	99.99 @10	99.91	99.99	99.99
	7.6	0.5	99.51 @1	99.99 @ 8	99.73	-[a]	99.98
S-FN-3-50-5	0.4	2.8	99.80 @6	99.86 @10	99.84	99.81	99.84
	1.2	0.6	99.21 @4	99.99 @ 8	99.46	99.52	99.98
S-FN-5-30-5	8.2	10.0	99.84 @6	99.99 @ 3	99.99	99.86	99.90
	8.2	5.7	99.20 @3	99.95 @10	99.38	99.54	99.90
R-WN-3-30-5	7.8	4.5	99.87 @3	99.99 @10	99.92	99.96	99.99
	7.8	3.2	99.08 @4	99.98 @10	99.50	99.55	99.96
R-WN-3-30-20	7.6	3.8	99.89 @4	99.99 @10	99.95	99.93	99.99
	7.5	4.7	99.92 @3	99.99 @10	99.93	99.96	99.99
R-WN-3-50-5	7.3	7.1	99.97 @4	99.99 @10	99.98	99.98	99.99
	7.2	5.9	99.97 @5	99.98 @10	99.99	99.98	99.98
R-WN-5-30-5	8.4	7.0	99.67 @5	99.96 @1,10	99.92	99.71	99.90
	8.2	9.6	-[a]	-[a]	-[a]	-[a]	-[a]
R-FN-3-30-20	7.8	4.8	99.97 @4	99.99 @ 8	99.98	99.98	99.99
	7.6	4.9	99.85 @4	99.99 @ 8	99.95	99.88	99.99
R-FN-3-30-40	7.7	2.3	99.80 @3	99.99 @10	99.87	99.93	99.99
	7.6	3.5	97.15 @4	99.99 @10	99.76	98.94	99.98
R-FN-3-50-40							
R-FN-3-50-40	8.0	3.2	99.95 @7	99.99 @ 1	99.99	99.96	99.96
	8.0	1.9	97.90 @4	99.99 @10	99.89	99.12	99.99

[a] Indicates test conditions which had apparent fractional efficiencies >100%.

conditions tested, collection performance was equivalent and maximum, and it thus does not provide a basis for ranking the four combinations of cleaning mode and bag type.

In the present test series a considerable amount of bag pressure drop (dp) data was obtained, summarized as average values in Table 9. The results show marked differences in bag dp both within and between mode/bag groups. The variation within groups is in the direction expected in response to changing test conditions. A comparison of results between cleaning modes clearly shows shake mode operating at significantly lower dp. In other words, shake appears to provide considerably more efficient cleaning than reverse flow.

TABLE 9. PRESSURE DROP RESULTS

Run	ΔP_e	ΔP_r	S_e	S_r	K
S-WN-3-30-5	0.60(2.4)	1.00(4.0)	40.2(0.82)	65.1(1.33)	33,400(33.9)
S-WN-3-50-5	0.52(2.1)	0.95(3.8)	34.8(0.71)	61.7(1.26)	25,100(21.6)
S-WN-5-30-5	1.44(5.8)	1.94(7.8)	56.8(1.16)	75.9(1.55)	18,300(15.7)
S-FN-3-30-5	0.17(0.7)	0.40(1.6)	11.3(0.23)	26.0(0.53)	29,400(25.3)
S-FN-3-50-5	0.32(1.3)	0.70(2.8)	21.1(0.43)	45.6(0.93)	29,400(25.3)
S-FN-5-30-5	0.67(2.7)	1.29(5.2)	26.9(0.55)	50.9(1.04)	28,700(24.7)
R-WN-3-30-5	0.65(2.6)	1.17(4.7)	42.1(0.86)	76.4(1.56)	32,900(28.3)
R-WN-3-30-20	0.90(3.6)	1.19(4.8)	58.8(1.20)	78.4(1.60)	18,700(16.1)
R-WN-3-50-5	0.85(3.4)	1.37(5.5)	55.4(1.13)	89.6(1.83)	19,800(17.0)
R-WN-5-30-5	1.84(7.4)	2.44(9.8)	72.5(1.48)	96.0(1.96)	13,700(11.8)
R-FN-3-30-20	1.54(6.2)	2.07(8.3)	99.4(2.03)	135.2(2.76)	35,100(30.2)
R-FN-3-30-40	1.94(7.8)	2.31(9.3)	128.4(2.62)	153.8(3.14)	25,100(21.6)
R-FN-3-50-40	1.97(7.9)	2.44(9.8)	129.3(2.64)	159.2(3.25)	19,100(16.4)

Where ΔP_e = Effective pressure drop, kPa (in. w.c.)
ΔP_r = Residual pressure drop, kPa (in. w.c.)
S_e = Effective drag = $\Delta P_e/U$, kPa/m/s (in. w.c./fpm)
S_r = Residual drag = $\Delta P_r/U$, kPa/m/s (in. w.c./fpm)
K = Cake specific resistance, kPa/m/s • kg • m^2 (in. w.c./fpm-lb-ft^2)

For comparable filtration velocities and periods, the four mode/bag groups can be ranked in order of ascending residual pressure drop (ΔP_r) as follows:

	3-30	3-50	5-30
S-FN	0.40(1.6)	0.70(2.8)	1.29(5.2)
S-WN	1.00(4.0)	0.95(3.8)	1.94(7.8)
R-WN	1.19(4.8)	1.37(5.5)	2.44(9.8)
R-FN	2.07(8.3)	2.44(9.8)	-- --

In comparing bag types in the above ranking, as well as in Table 9, the following paradox appears. In reverse mode, felted Nomex operates at higher dp than woven Nomex. This might be expected since reverse cleaning is relatively inefficient and felted material is difficult to clean compared to woven material. However, opposite results are observed in shake mode. A tentative explanation for this reversal follows. Felted Nomex, having much greater permeability than woven, should operate at lower dp. If the cleaning mode is very efficient, the felted bag may well retain its high permeability; and shake cleaning has been shown to be considerably more efficient that reverse cleaning.

It is generally considered that collection efficiency is a direct function (nonlinear) of bag dp. In the present case, it is noted that incremental changes in bag dp had negligible effect on collection efficiency. This further supports the contention that the bags operated at maximum efficiency under all test conditions. It also implies that high collection efficiency might also be obtained at lower bag dp at conditions outside the test regimen.

3.1.2.7 Operating Problems--
A plague of mechanical malfunctions of the baghouse systems descended on the operation almost coincidentally with start of operations. Since operating problems from this source have been detailed before, it would be monotonous to repeat the descriptions here. Overall attrition of the baghouse unit is so severe as to dictate major overhaul before its return to the field.

One type of operating problem deserves comment since it relates to the application of baghouses to emission sources characterized by high moisture content in the gas; namely, mud deposit caused by condensation. At both the lime kiln and recovery boiler, dew point of the stack gas was about 66°C (150°F). Any substantial leakage of ambient air into the slipstream cools the gas below its dew point, and the resultant combination of condensate and solid particulate deposits mud throughout the baghouse system, especially in the bags. This is disastrous since the bags must be replaced and conditioned. At the lime kiln, with a relatively short run of accessible ducting (ca. 16.8 m) and high stack gas temperature (260°C-288°C), it was relatively uncomplicated to detect and stop significant leaks, and the high temperature gas kept the system hot after relatively rapid preheat of the system with a space heater.

At the recovery boiler, the stack gas temperature was lower (ca. 177°C) and most of the duct run was not readily accessible for leak testing (see Figure 3). When, finally, it was judged that significant leakage had been stopped, it was found that no manner of adding heat to the system at the baghouse end of the duct was adequate to maintain gas reaching this area above its dew point. It was ultimately necessary to take a space heater to the roof of the boiler, tee it into the duct at the stack port

and pull hot gas from the heater through the entire system for 1 to 2 hours in order to bring the system to high enough temperature to maintain the ensuing stack gas above its dew point throughout.

A third type of operating problem, encountered after resolution of the condensation problem, related to rapid loading of the bags, excessive bag dp, and ultimate restriction of flow through the baghouse. The end result occurred within 2 to 3 minutes after start of filtration. While grain load at the boiler did not appear to be excessive, the solids visually appeared much finer than those at the lime kiln. It seemed reasonable that some combination of filtration period and cleaning period would permit operation, but to determine this combination required execution of a fractional factorial design. The optimum combination was determined as 10-min filtration, 20-s cleaning period, compared with 30 min and 5 s, respectively, proposed in the test plan. Bag dp was 1.24-2.49 kPa (5-10 in. w.c.).

Resolution of these two problems at the recovery boiler consumed approximately 4 weeks. On the verge of starting testing/sampling operations, No. 3 boiler suffered a series of malfunctions which shut it down at unpredictable times. After 2 or 3 days, when it became known that there would be no relief from this malady, the baghouse connection was switched to No. 4 boiler, where it was discovered that atypical performance of the cascade evaporators, upstream of the slipstream port, resulted in a cloud of black liquor beads in the stack gas entering the baghouse system. These conditions at the boilers, together with continued deterioration of the baghouse system overall, dictated termination of the test program.

3.1.2.8 Conclusions--
In control of lime kiln emissions, all cleaning mode/bag type combinations performed with maximum collection efficiency, i.e., both integrated mass and fractional, within the test regimen. The term "maximum" is used in view of the insensitive responses of collection efficiency to changes in test parameters.

Overall, integrated collection efficiency was 99.98+%. Overall averages of mean fractional efficiencies by size range were as follows:

Size, μm	Efficiency, %
1-3	99.815
4-6	99.814
7-10	99.918

On the basis of collection efficiency, it appears that a high level of control of lime recovery kiln emissions can be afforded by a baghouse.

On the basis of bag differential pressure at comparable operating conditions, shake cleaning was significantly more efficient than reverse flow cleaning.

The choice of baghouse control of lime kiln emissions cannot be based on collection efficiency alone. On the contrary, projected operating problems tend to discourage use of a baghouse in this application. The specific problems are the high moisture content of the flue gas, the probable frequency at which condensation and mud deposition can occur, and the necessity for an auxiliary preheat system to prevent this disastrous result. Such a system would add both cost and complexity to the control installation.

At the outset of this study the lime recovery kiln effluent was expected to be similar to that from dry process cement kilns. In fact, the lime kiln tested more closely resembles a wet process cement kiln whose stack gas also has a high moisture content; 20% to 25%. It is notable that wet process cement kilns largely employ electrostatic precipitator (ESP) units for emission control since the moisture enhances ESP performance, and high temperature obviates condensation problems. In dry process plants, baghouses are occasionally used as secondary collectors, preceded by some type of mechanical collector. Glass bags appear to be the norm. Collection efficiencies are noted as 99.8+%, essentially equivalent to efficiency reported herein for Nomex bags at the lime kiln. (In general, see References 3 through 7.)

The fact that the wet and dry process cement kilns require different types of control devices supports the rationale discouraging use of a baghouse for control of lime recovery kiln emissions. The same rationale would apply to use of a baghouse at the recovery boiler where moisture content of the flue gas is also at a high level.

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[4]Gilliland, J. L. Air Pollution Control in the Portland Cement Industry. 1st Air Pollution Control Conference. April 1971.

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[6]Squires, B. J. Fabric Filter Dust Collectors, Their Use in the Ventilating, Steel, Non-Ferrous Metals, Cement, Power and Chemical Industries. Filtration and Separation, pp. 228-239, May/June 1967.

[7]Tripler, A. B., Jr., and G. R. Smithson, Jr. A Review of Air Pollution Problems and Control in the Ceramic Industries. American Ceramic Society, Columbus, Ohio, May 5, 1970.

3.1.3 Baghouse Repackaging and Upgrading

After conclusion of testing at the Weyerhauser pulp mill, the baghouse was returned to Research Triangle Park, North Carolina for a complete repackaging and refurbishing effort.

As received, the baghouse unit was mounted in a 1.36-metric-ton (1.5-ton), stake bed truck. Portions of the system were relocated for operation outside the truck bed due to the truck size. This mode of operation turned out to be extremely inconvenient and detrimental to efficient field testing. Therefore, it was decided to mount the entire baghouse system in a 12.2-m (40-ft) tractor-trailer unit.

The trailer unit was purchased and delivered on 30 January 1976, and repackaging commenced. In addition to transfer of the system to the trailer, potential solutions to a number of operational problems encountered during field operations were incorporated. Figures 4 and 5 show the current baghouse unit.

As of this writing, the baghouse unit is scheduled to replace the mobile scrubber system on a gray iron foundry effluent some time during September 1976.

3.2 MOBILE SCRUBBER UNIT

3.2.1 Background

The mobile scrubber unit was designed and fabricated by the Detection Branch, Chemical and Biological Sciences Division of the Naval Surface Weapons Center (NSWC), Dahlgren, Va., under project order No. 4-0105-(NOL)/EPA-1AG-133(D), Task 2. On completion of construction and brief equipment checkout by NSWC, the unit was received by the Industrial Environmental Research Laboratory on 16 December 1974. The unit was subsequently placed on site at Pennsylvania Power & Light Company's generating station at Sunbury, Pa. on 15 January 1975, for initial field shakedown testing. Shortly after startup of the unit at Sunbury the induction fans failed, and NSWC retrieved the unit to determine the cause of failure and repair the fans.

After completion of repairs and minor modifications, the unit was returned to IERL and taken to the Research Triangle Park for extensive shakedown tests under simulated field conditions. It was then taken to Weyerhauser Corporation's pulp mill at Plymouth, N.C., on 21 April 1975, and hooked up to a lime recovery kiln for execution of a test plan for evaluating dust control efficiency of the two types of scrubbers involved (venturi and sieve tray). Before a week of operation under field conditions was completed, the induction fans failed once more.

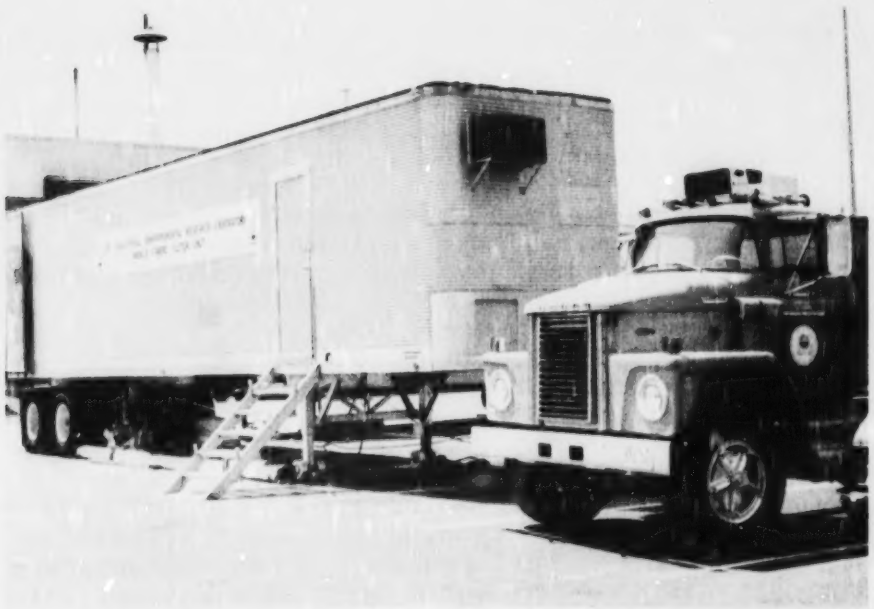

Figure 4. Current baghouse enclosure.

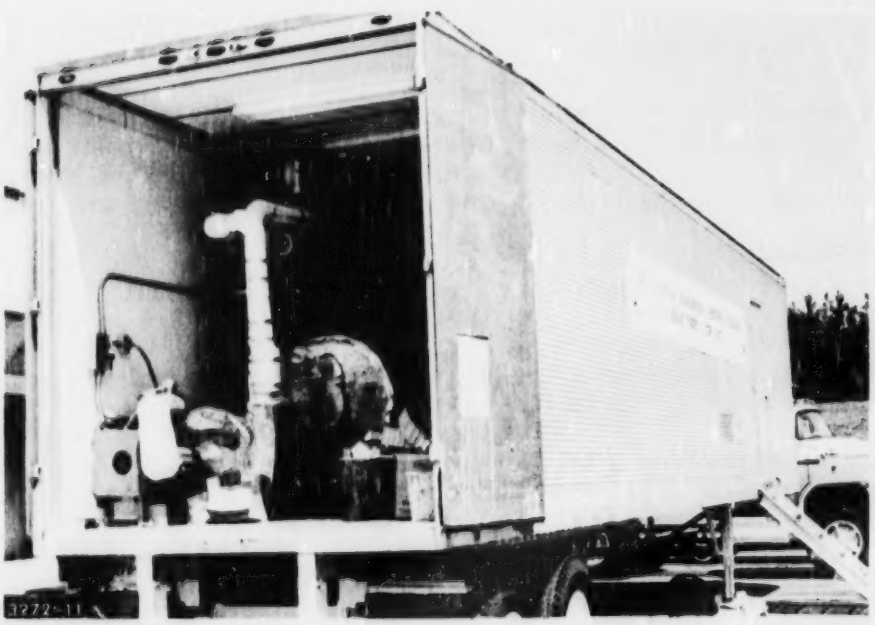

Figure 5. End view - baghouse.

3.2.2 Events of Second Year

After the blowers had failed for the second time, the scrubber unit was returned to Research Triangle Park, N.C. for modifications. New blowers of a different design were selected, purchased and installed in the scrubber unit. These items were received from the vendor during January 1976.

Carryover liquid had also been noted as an operational problem with the scrubber system, and the decision was made to replace the mist eliminator with another unit of different design to try and minimize this occurrence.

A third bothersome operational problem involved activation of automatic shutdown sequence due to false signaling from the sump tank overflow protection system. The cause turned out to be entrained mist. This problem was remedied by design change.

After the new equipment had been installed, the scrubber unit was subjected to simulated field testing at Research Triangle Park for 2 weeks. No problems surfaced during the testing, and a concerted effort was then initiated to find a suitable testing site.

In mid-June 1976, arrangements were finalized to place the scrubber on stream at a gray iron foundry, and at the time of this writing field testing is underway. Figures 6 through 9 illustrate the scrubber unit configuration.

3.3 MOBILE ENERGY VAN

The EPA Energy Van is an energy research unit designed and constructed by Englehard Industries for the U.S. Environmental Protection Agency. It contains energy supply systems for the home which are designed to be environmentally clean and energy conserving.

Integrated systems include fuel cells, a solar energy collector, a heat pump, and catalytic appliances. These systems provide the energy needed to heat space and water, and to cool, ventilate, cook, light, operate appliances, and refrigerate within the van. Figures 10 through 12 illustrate the van configurations.

Objectives in building the van were to develop and demonstrate an energy supply system which cuts pollution and energy consumption by as much as 50% for residential and commercial buildings.

This mobile unit was acquired by the contractor on 21 June 1976. At the time of this writing, a testing program covering the period 1 September 1976 through 30 June 1977 is being written. The unit will be operated at the Environmental Research Center,

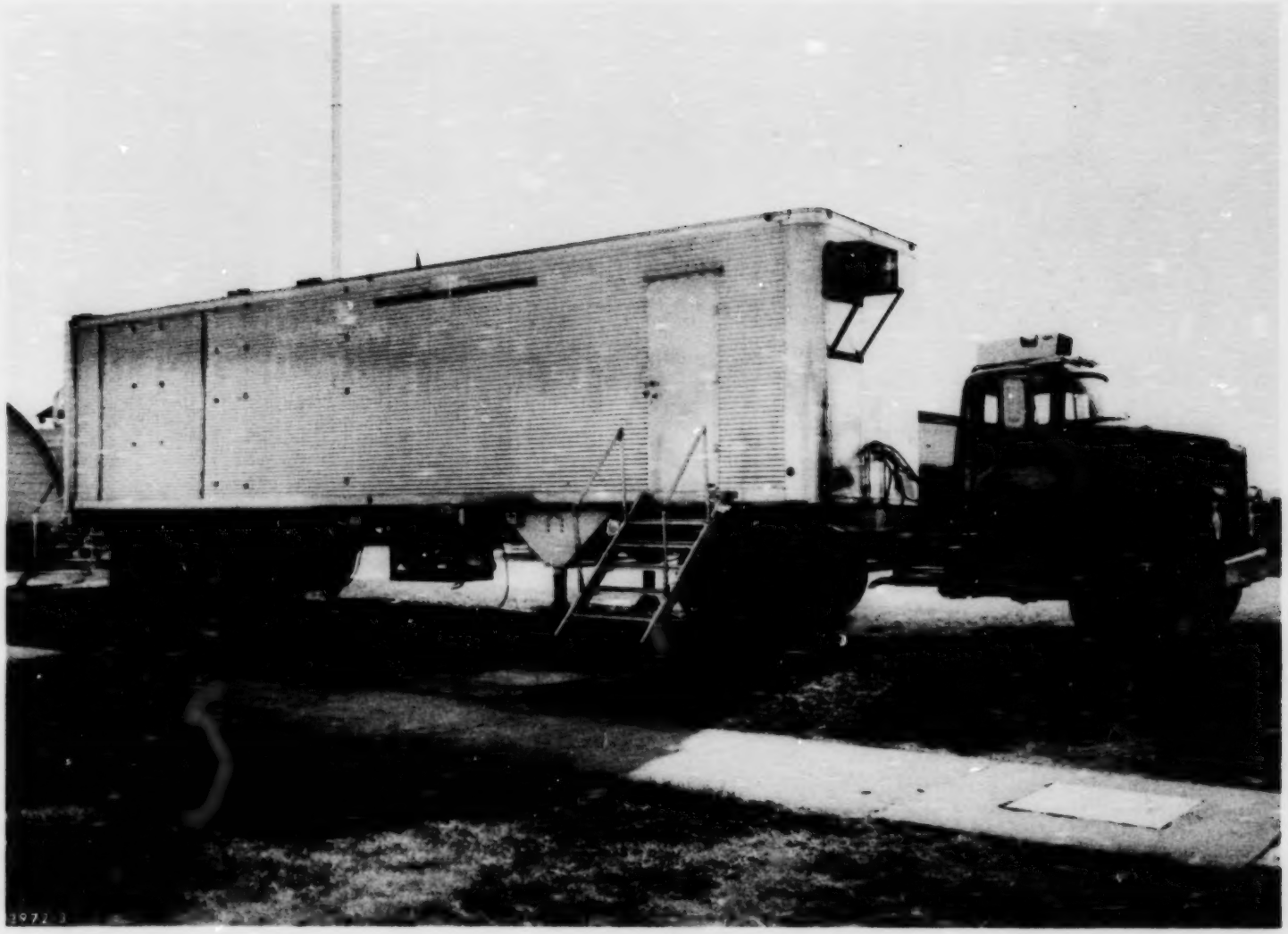

Figure 6. External view of mobile scrubber unit.

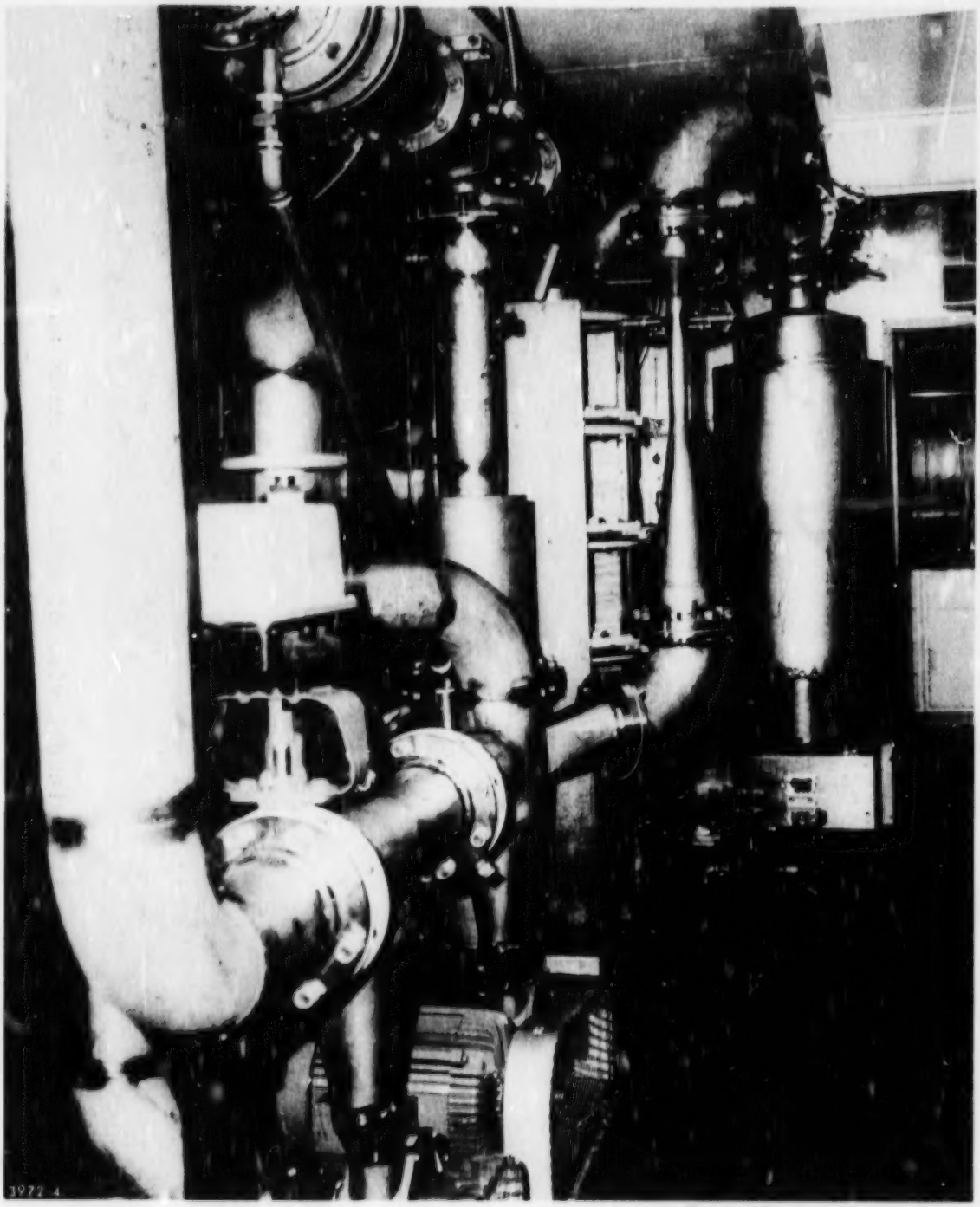

Figure 7. Mobile scrubber unit process area.

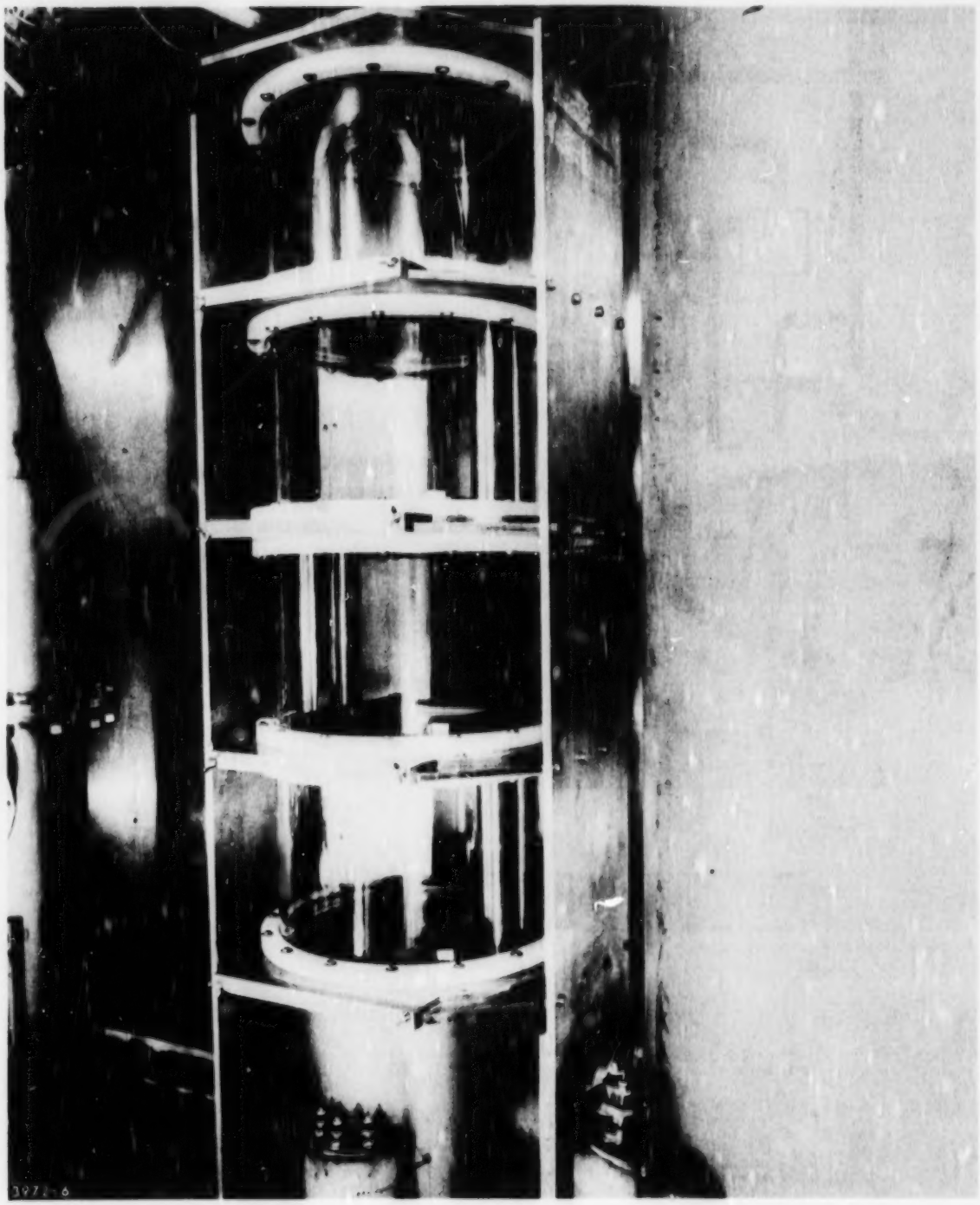

Figure 8. Sieve tray column.

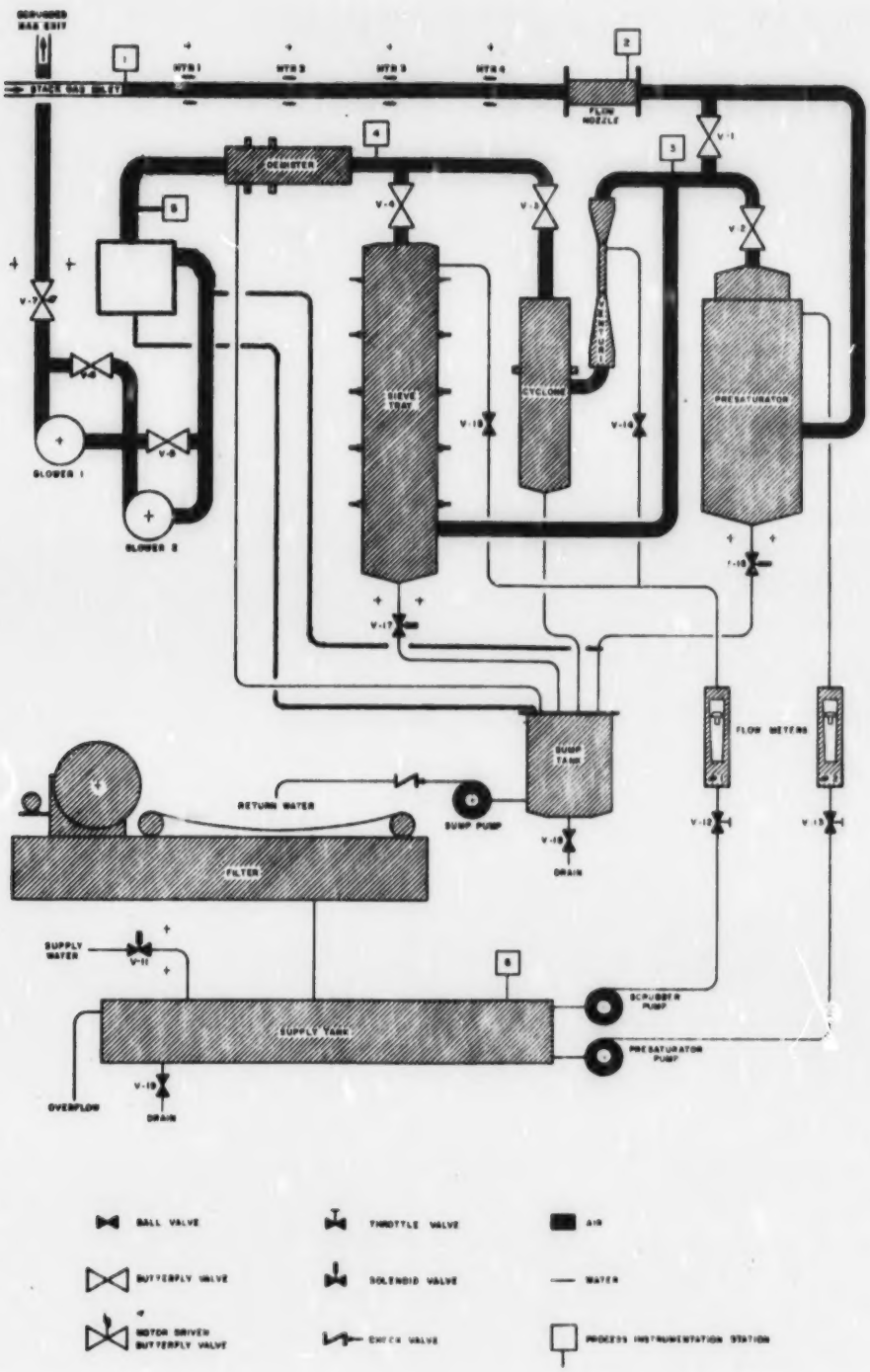

Figure 9. Scrubber flow schematic.

Figure 10. Energy van - side view.

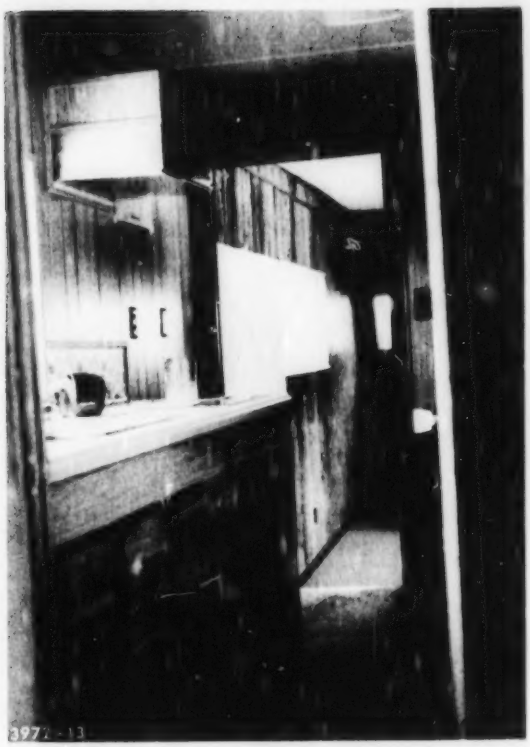

Figure 11. Energy van - interior living area.

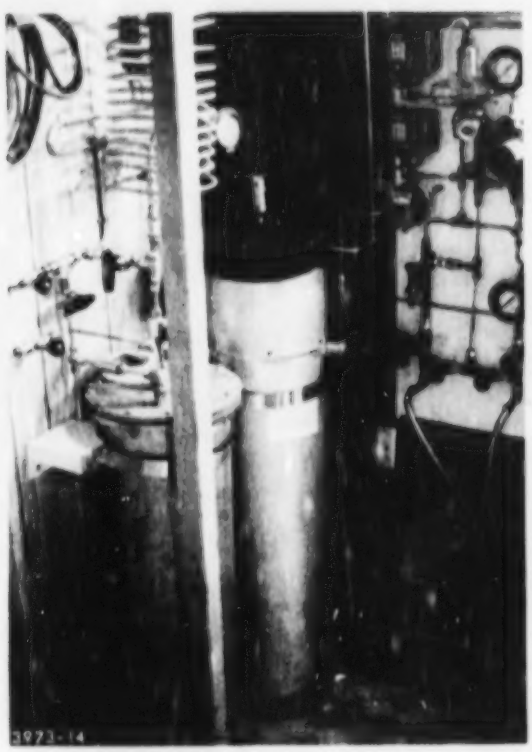

Figure 12. Energy van - fuel delivery system.

Research Triangle Park, North Carolina, during the testing program period. A separate final report will be issued for this unit at the end of the testing program.

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